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INTERACTION STUDIES OF LASER BEAMS  
INTERSECTING IN AN ACTIVE MEDIUM  
(Crossed Beam Laser)

Third

Semi-Annual Technical Summary Report

1 February 1967 - 31 July 1967

ONR Contract No. Nonr-5034(00)

Project Code No. 4730

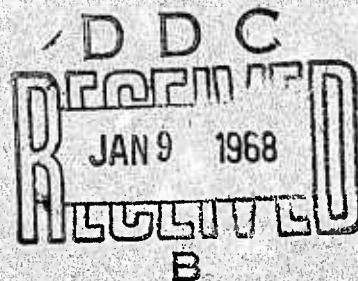
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Prepared for

Office of Naval Research  
Department of Navy  
Washington 25, D. C.

Prepared by

Research and Development Center  
General Electric Company  
Schenectady, N. Y. 12301



INTERACTION STUDIES OF LASER BEAMS  
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Semi-Annual Technical Summary Report

1 February 1967 - 31 July 1967

Program Manager

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Submitted by

Heavy Military Electronics Department  
General Electric Company  
Syracuse, New York

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## Section I

### SUMMARY

The interaction amplifier experiment using a low power (7 megawatt, 0.5 joule) Q-switched perturbing laser was operated. Although the perturbing laser output energy of 0.5 joule was lower than that calculated to extract 67% of the stored energy in the interaction amplifier, a 20% decrease in amplifier gain was achieved.

Initial streak photographs showed that strong coupling existed between the unpolarized probe and the polarized perturbing lasers. The coupling was reduced significantly by polarizing the probe laser beam at right angle to that of the polarized perturbing laser beam. Nevertheless, "frequency pulling" was observed whereby the frequency of the probe laser output was pulled by the signal injected from the Q-switched perturbing laser.

It has been shown that energy is transferred across the neodymium inhomogeneously broadened line in much less than 70 nanoseconds.

Two refinements of the experiment were undertaken to improve the chances of making quantitative measurements of the energy transfer rate. One was the design, construction, and testing of a new higher power (250 megawatt, 5 joule) Q-switched perturbing laser, and the other was the design and construction of an optical isolator for the probe laser.

The shape of the fluorescence line and the wavelengths of peak gain of several Nd glasses were measured.

## Section II

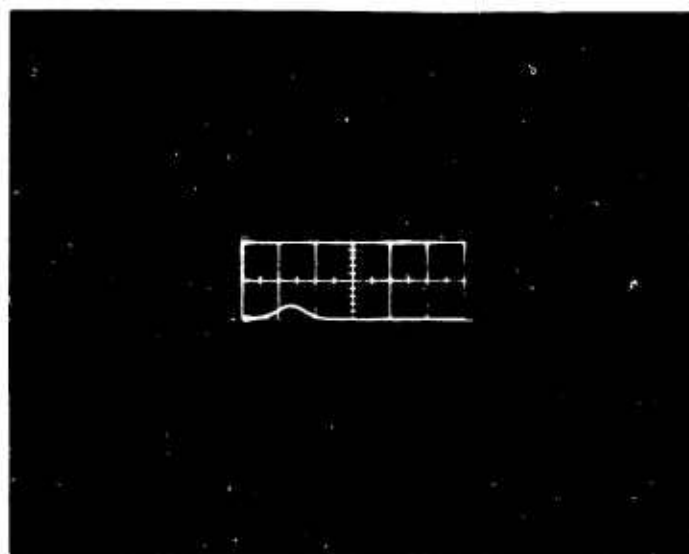
### WORK PERFORMED

#### A. INTERACTION AMPLIFIER EXPERIMENT

##### 1. Low-Power Q-Switched Perturbing Laser

The interaction amplifier experimental arrangement shown in Figure 2 of the Second Semi-Annual Technical Summary Report was completely "debugged" and successfully operated under a variety of conditions. The Q-switched perturbing laser employed a 0.5"D x 6.0"L Nd-doped glass rod and is referred to as a "low-power" laser to distinguish it from a subsequently used higher power laser using longer rods. The output beam from the low-power Q-switched perturbing laser was detected and a Tektronix 519 oscilloscope was used to record the output as shown in Figure 1. The output pulse length is 70 nanoseconds and the energy is 0.5 joules. Considering the losses in this Q-switched laser which includes a spectral mode selector the 0.5 joule output is believed to be a reasonable value. The spectral output was recorded and this is shown in Figure 2. The output spectra is less than 10 angstroms wide and is centered at 10,560 Å which is near the peak of the gain curve.

Based on the calculations given on page 5 of the Second Semi-Annual Technical Summary Report, the present 0.5 joule output is appreciably smaller than the 1.5 joules required to extract 67% of the stored population inversion. Nevertheless, it was expected that a measurable decrease in amplifier gain could be achieved so that the experiments were continued. The relative timing of the various components such as the probe laser, Q-switched perturbing laser, interaction amplifier laser, Kerr cell, oscilloscope, and streak camera is shown in Figure 3. Many interaction experiments were observed and a typical streak photograph of the spectra is shown in Figure 4. It is noted that the Q-switched perturbing laser had Eigen wavelengths which matched those of the probe laser; this is deduced from the brightening of the probe laser spectra during the Q-switched



Time Scale  
100 nanoseconds  
per major division

Fig. 1. Low-Power Q-Switched Perturbing Laser Output Pulse

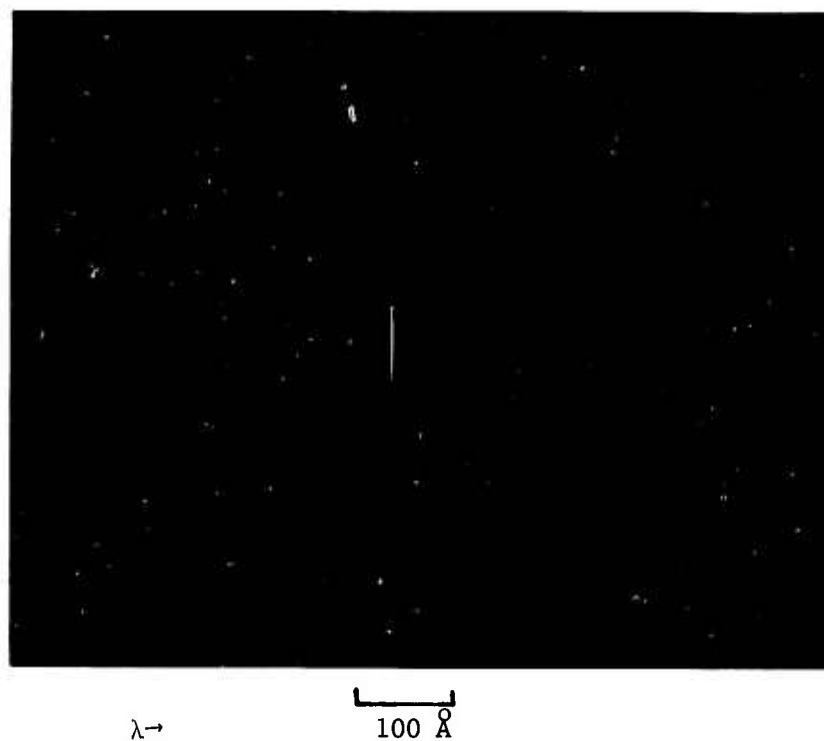


Fig. 2. Typical Streak Photograph of the Low-Power Q-Switched Perturbing Laser Output Pulse



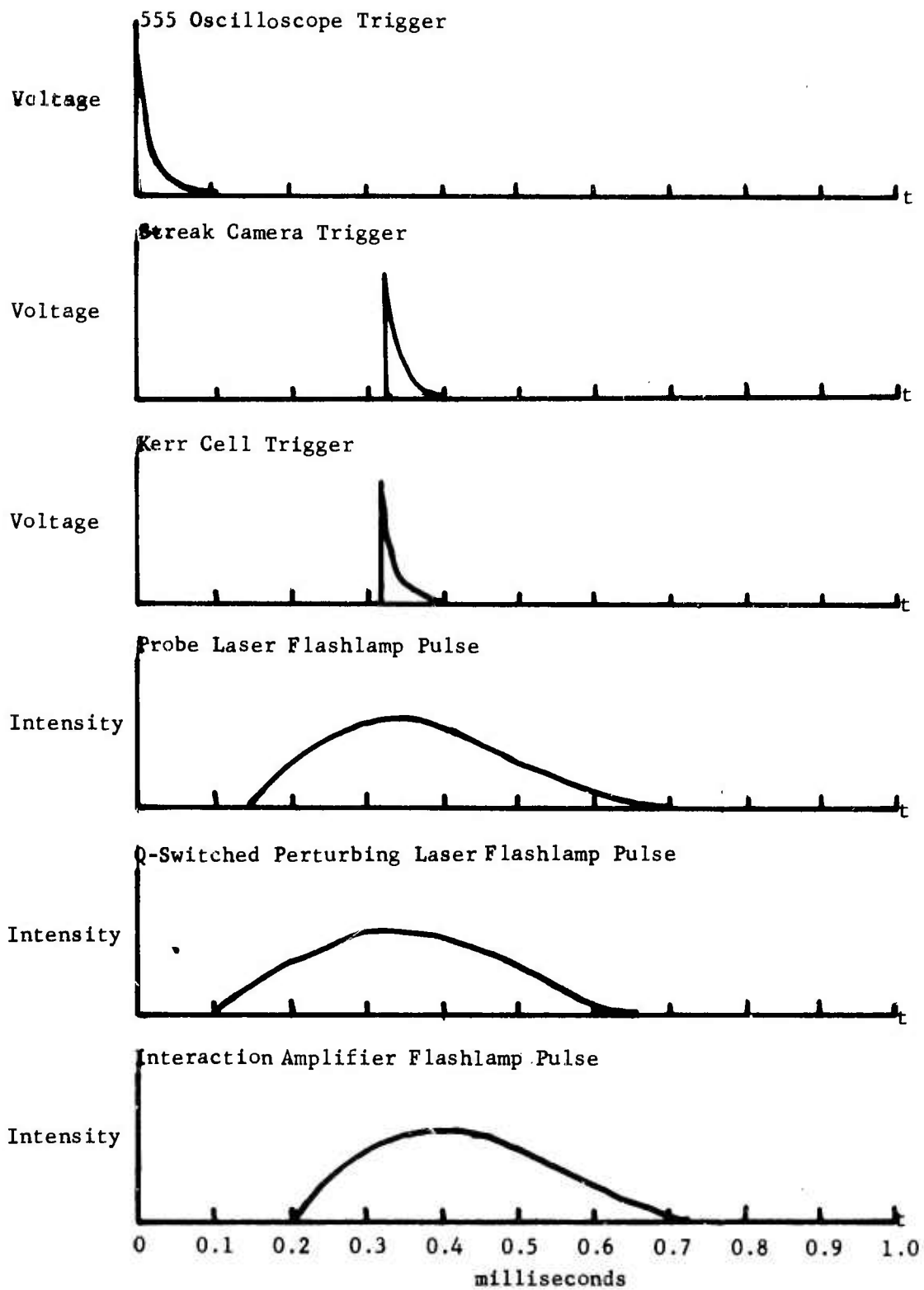


Fig. 3. Relative Timing Diagram

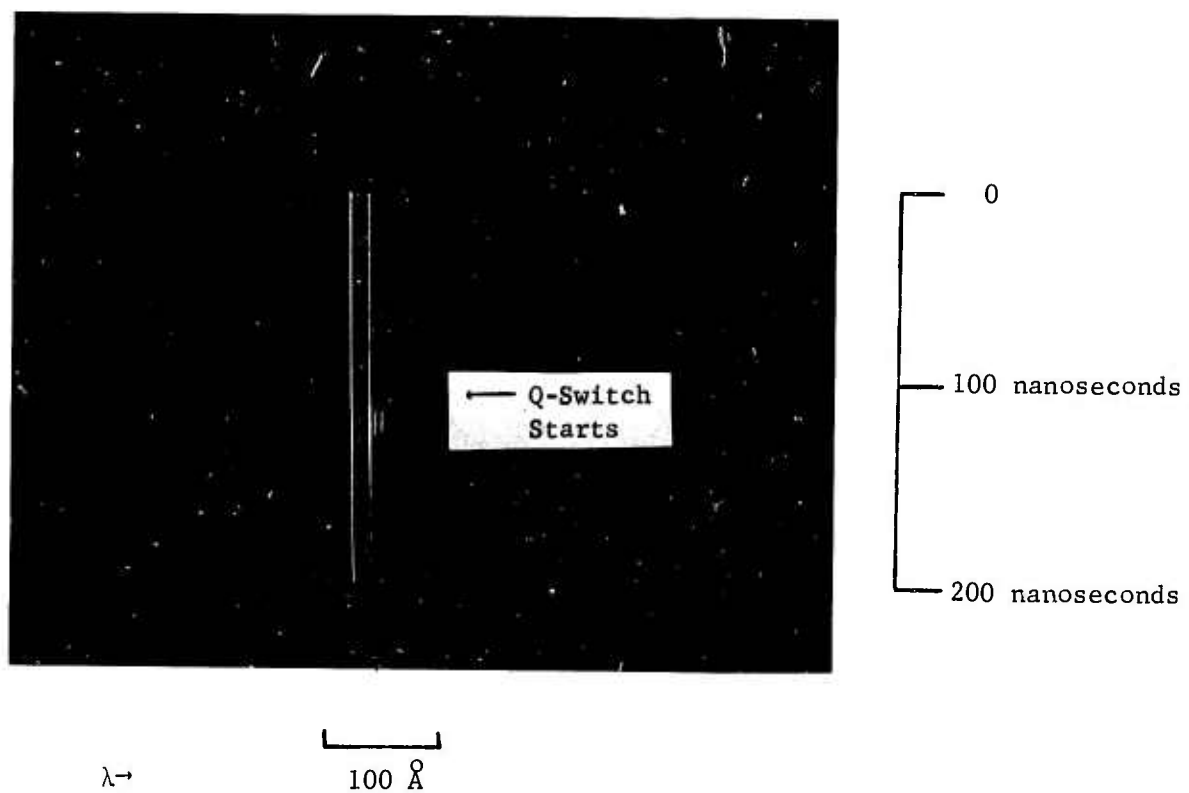


Fig. 4. Streak Photograph Showing Coupling of the Probe and Q-Switched Perturbing Lasers

pulse. It is to be noted that if the Q-switched perturbing laser is operated alone, its spectra consisted of a single wavelength as discussed above and shown in Figure 2. This result indicates that coupling exists between the probe and Q-switched lasers. The Q-switched laser beam is polarized because of the Kerr cell, but the probe laser beam is unpolarized. Thus any reflection and scattering from the interaction amplifier can provide coupling between the probe and Q-switched lasers.

In order to reduce the amount of coupling, a polarizer was inserted in the probe laser Fabry-Perot cavity with the polarization of the probe beam was orthogonal to that of the Q-switched laser beam. Streak photographs were taken and these showed that the coupling was reduced since the Q-switched laser output wavelength did not match those of the probe laser. A typical streak photograph is shown in Figure 5. It was observed that after the Q-switched perturbing pulse passed through the interaction amplifier, the brightness or intensity of the probe beam spectra reduced by about 20% from its initial value. This indicates that the population inversion or gain of the amplifier decreased. The 20% reduction in amplifier gain is an approximate value because of scattering in the densitometer and lack of calibration. Since each of the probe laser spectral lines decreased by about the same amount of 20%, regardless of the wavelength difference from the Q-switched laser wavelength, it is concluded that the energy transfer time must be appreciably shorter than 70 nanoseconds which is the pulse length of the Q-switched perturbing laser beam.

In the preceding experiment a change in probe laser wavelengths was noted for the duration of the Q-switched perturbing laser pulse. Two streak photographs showing this effect are shown in Figure 6. The shift in wavelength or "frequency pulling", is towards the Q-switched laser wavelength, and it was found to shift by as much as  $5 \text{ \AA}$ . This effect was unexpected because the beams were orthogonally polarized. Further experiments were carried out to determine whether the effect was real, or was caused by the instrumentation.

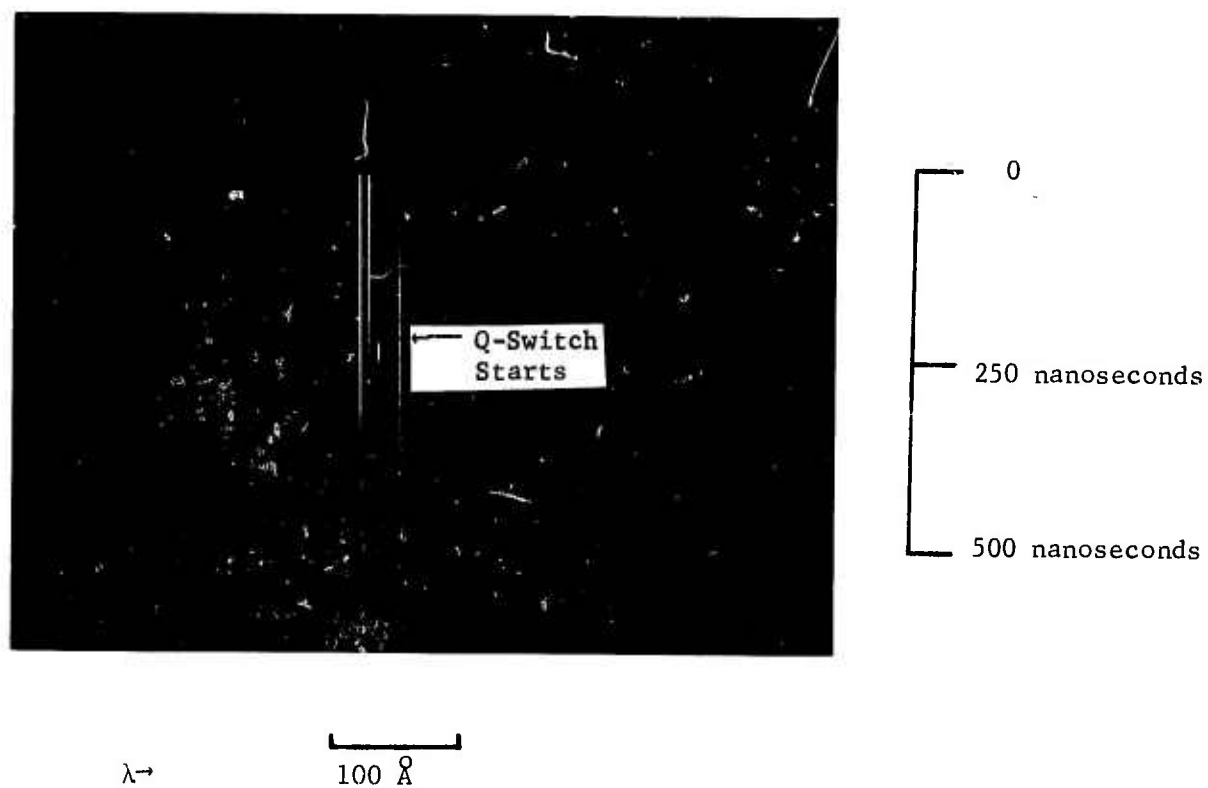


Fig. 5. Streak Photograph Showing the Probe Laser and Q-Switched Perturbing Laser

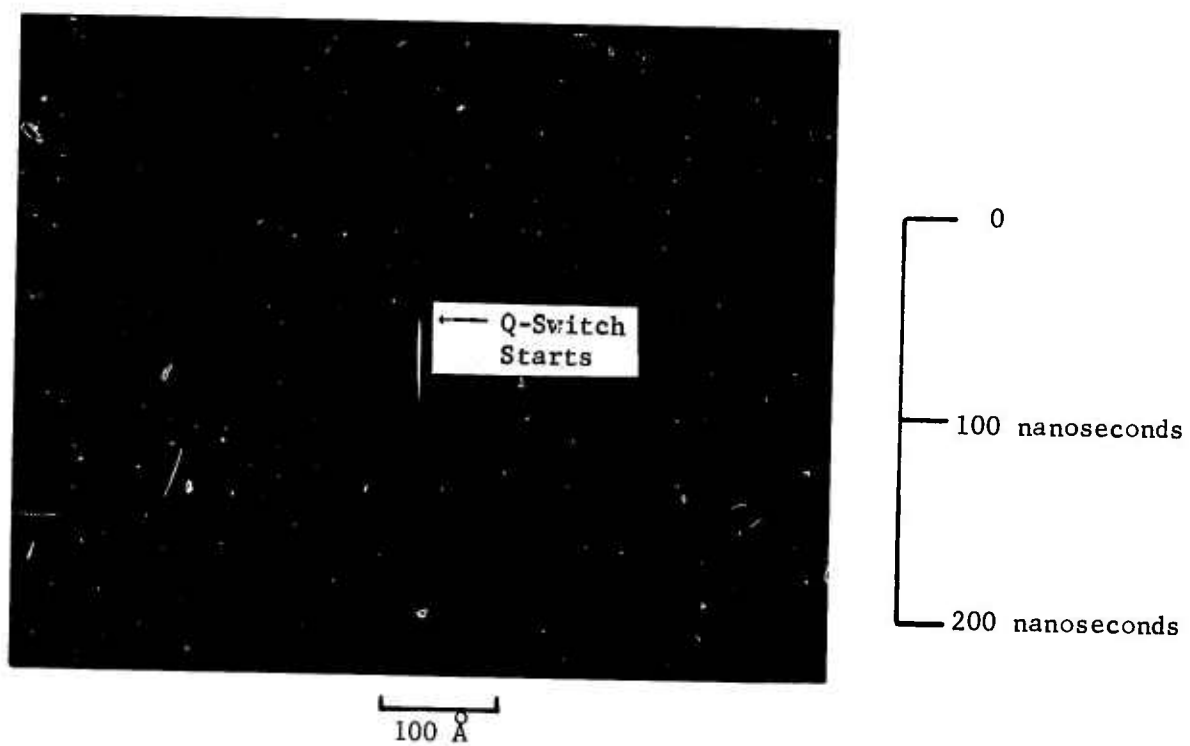
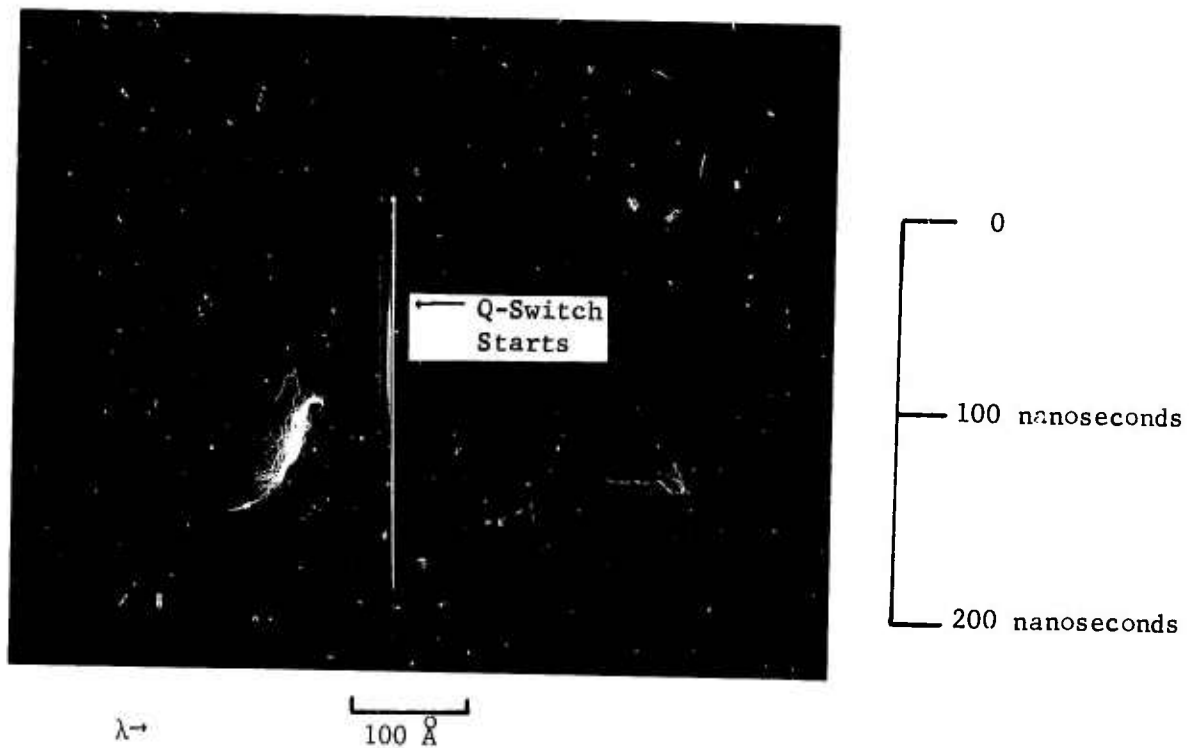


Fig. 6. Two Streak Photographs Showing Frequency Pulling Effect

In the first experiment, the entire system was operated as usual except the perturbing laser beam was deflected out of the system. This was an attempt to determine whether or not there were any extraneous coupling effects in the electronic circuits. A streak photograph taken showed the probe beam spectra without any shift during the Q-switched perturbing laser beam pulse.

In the image-converting camera, there are as many electron beams as there are line spectra. At extremely high electron beam currents, it is possible for co-directional beams to attract due to self-constricting magnetic fields. However calculations have shown that the electron beam currents are well below the self-constricting values.

Finally, the experiment was repeated without pumping the interaction amplifier rod. No frequency pulling was observed. As the interaction amplifier was pumped, frequency pulling was first noted when the interaction amplifier single-pass gain was 4 dB. Most of the experiments showing the frequency pulling effect were conducted with an amplifier gain of 5 dB. Power calculations have been carried out which essentially confirm that the frequency pulling effect is due to coupling or injection pulling, which is related to injection locking,<sup>(1)</sup> caused by reflections, signal amplification, and depolarization from stress birefringence in the pumped amplifier rod. The amplifier rod is tilted by about  $1/2^\circ$  to reduce the coupling but not so much as to affect the interaction volume.

In order to reduce the coupling which not only causes frequency pulling but may undesirably alter the intensity of the probe beam spectra, it was decided to design and build an optical isolator. This is described later in the report.

## 2. High-Power Q-Switched Perturbing Laser

The preceding discussion and interaction experiments have shown that a higher energy output from the Q-switched perturbing laser is desired. Also there is an

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(1)DeShazer, Johns Hopkins Conference, "Ions in Solids", September 1966

indication that the energy transfer time is appreciably shorter than 70 nanoseconds. In order to detect a short transfer time, it is desired that the Q-switched laser pulse duration be comparable with the transfer time. However high energy output with a very short pulse could easily damage the Q-switched laser. Thus a goal of 5.0 joules output in 20 nanoseconds was established as a reasonable compromise.

A new, high-power Q-switched perturbing laser was designed employing a double exfocal pump cavity.<sup>(2)</sup> This type of pump cavity is efficient and provides very uniform pumping. Laser rods which are 5/8" in diameter and longer than 18 inches can be pumped. Several Nd glass rods are available which meet these dimensional requirements.

A laser rod with  $10^\circ$  angle ends was used to reduce amplified spontaneous emission and permit higher population inversion levels. An optical schematic diagram of the Fabry-Perot cavity of the higher-power Q-switched perturbing laser is shown in Figure 7. A photograph of the double exfocal pump cavity is shown in Figure 8. With a 50-nanosecond pulse forming network (PFN) on the Kerr cell, this laser had an output pulse length of 20 nanoseconds and an energy output greater than 5.0 joules with 2200 joules input to the flash lamps. A typical output pulse is shown in Figure 9. The peak power density exceeds 0.6 gigawatts/cm<sup>2</sup>. When the input energy to the flash lamps exceeded 2200 joules, the laser with the Kerr cell closed, lased as a normal-pulse laser.

In order to obtain an output pulse shorter than 20 nanoseconds, a 10-nanosecond PFN was used to drive the Kerr cell. Although the Kerr cell could be turned on very fast (0.1 nanosecond), the Kerr cell did not close as expected due to deficiencies in the PFN.

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(2)D. Roess, Laser Lichtverstärker und -Oszillatoren, Akademische Verlagsgesellschaft, Frankfurt am Main, Germany (1966) p. 464

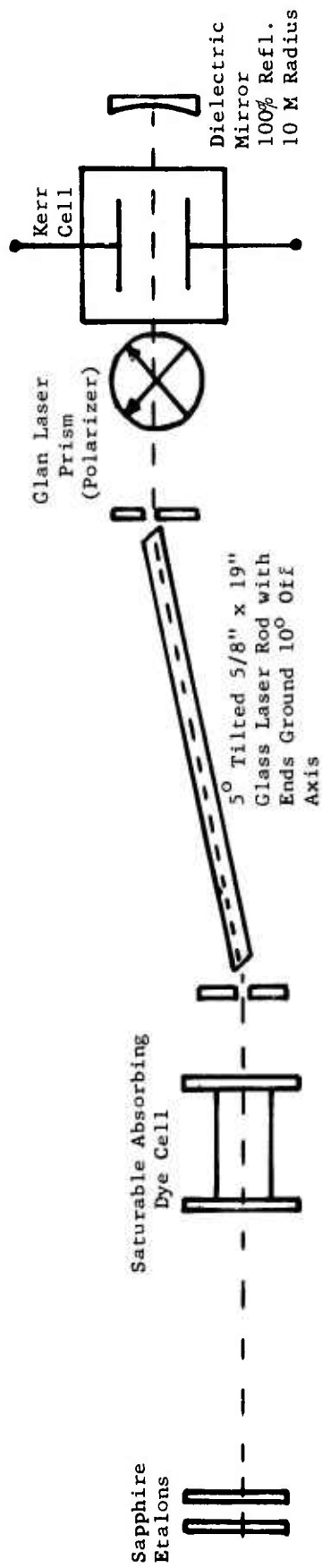


Fig. 7. Optical Schematic Diagram of High-power Q-switched Perturbing Laser



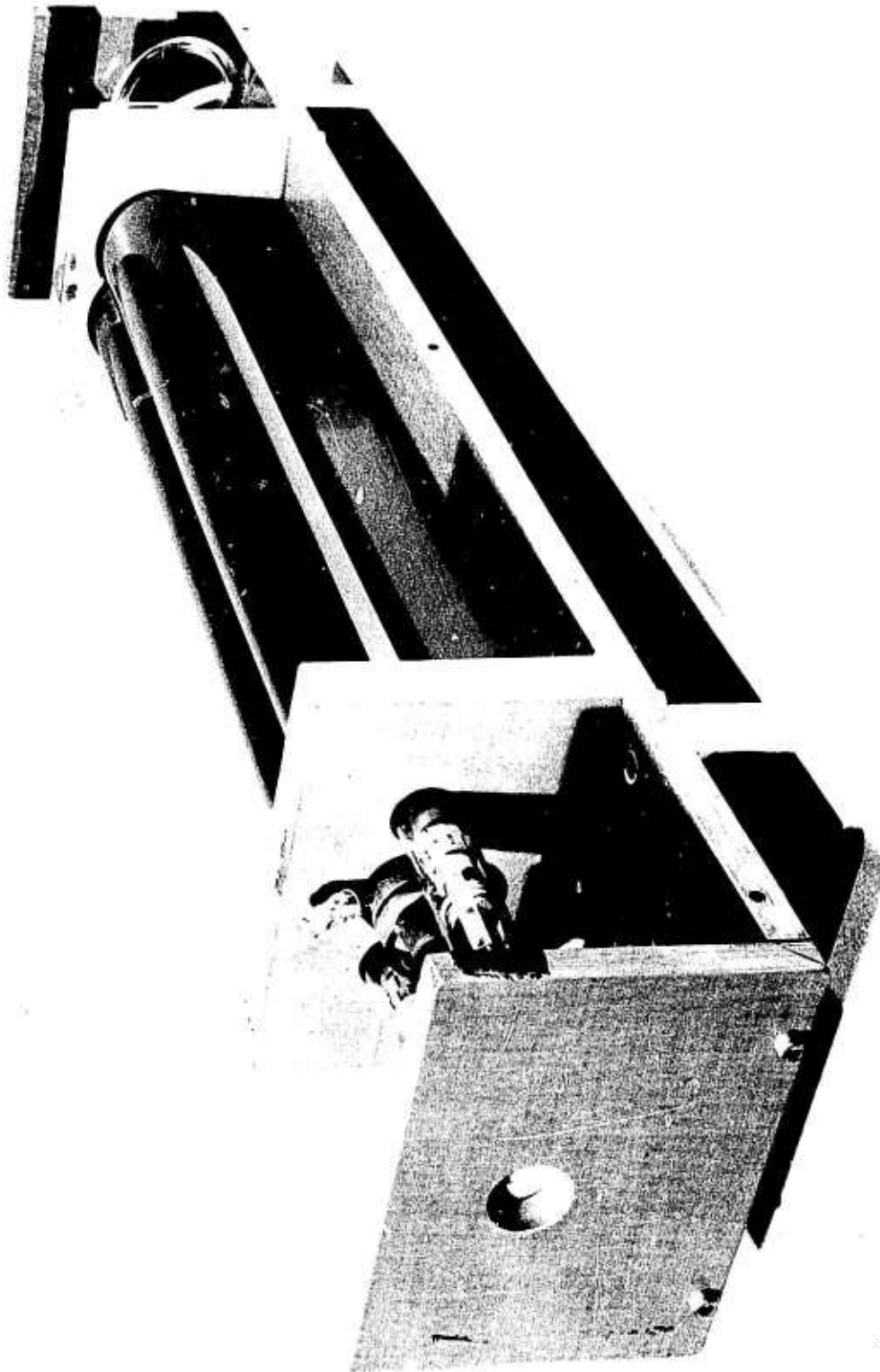


Fig. 8. High Power Q-Switched Perturbing Laser

Because of the high power densities produced by this laser, several polarizing prisms were damaged. All of these were Glan Laser prisms which are designed for high power densities. In some instances there were fractures in the calcite prisms, and in others the spacers located at the corners between prisms vaporized from the radiation. In cooperation with Special Optics Co., Cedar Grove, New Jersey, a high power polarizing prism is being fabricated employing x-ray selected calcite prisms and radiation resistant spacers. This prism will be available in the near future.

One should note that the photograph of the high-power Q-switched perturbing laser pulse in Figure 9 shows a slight structure. A calculation of the round trip time of the Fabry-Perot cavity exactly matches this structure. The presence of this structure could indicate that the perturbing laser is mode-locked.<sup>(3)</sup> Further study of the structure of the perturbing pulse should be carried out in order to interpret the measurement results using this laser.

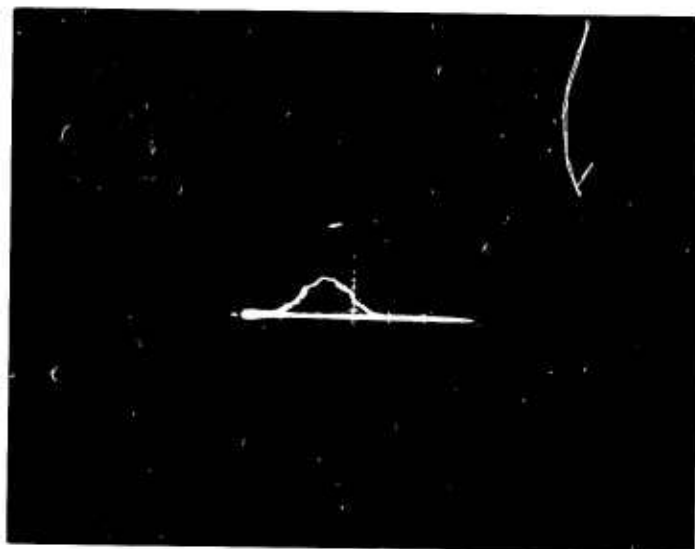
### 3. Optical Isolator

In order to decouple completely the probe and perturbing lasers, an optical isolator will be placed between the probe laser and the 50-50 beam splitter. (See Figure 2, page 9 of the Second Semi-Annual Technical Summary Report.) Among the glasses available with useful Verdet constants were the Schott SF-6 and SFS-6 glasses. The SFS-6 glass has the larger Verdet constant but the delivery time was too long for the present isolator. Thus a 5/8"D x 7"L SF-6 glass rod was procured; it was found to have excellent optical quality.

An isolator was built and a photograph of it is shown in Figure 10. There is a 10" long, 2880 turn, 10 ohm solenoid to provide the longitudinal magnetic field. It is expected that 50 amperes of current will produce sufficient field to rotate a 1.06  $\mu$  polarized beam by 45°. Since the solenoid is not cooled, its

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(3)M.A. Dugay et al, Phys. Rev. Letters 19, p. 1014 (1967)



20 nanoseconds  
per major division

Fig. 9. Typical Output Pulse of the High-Power Q-Switched  
Perturbing Laser

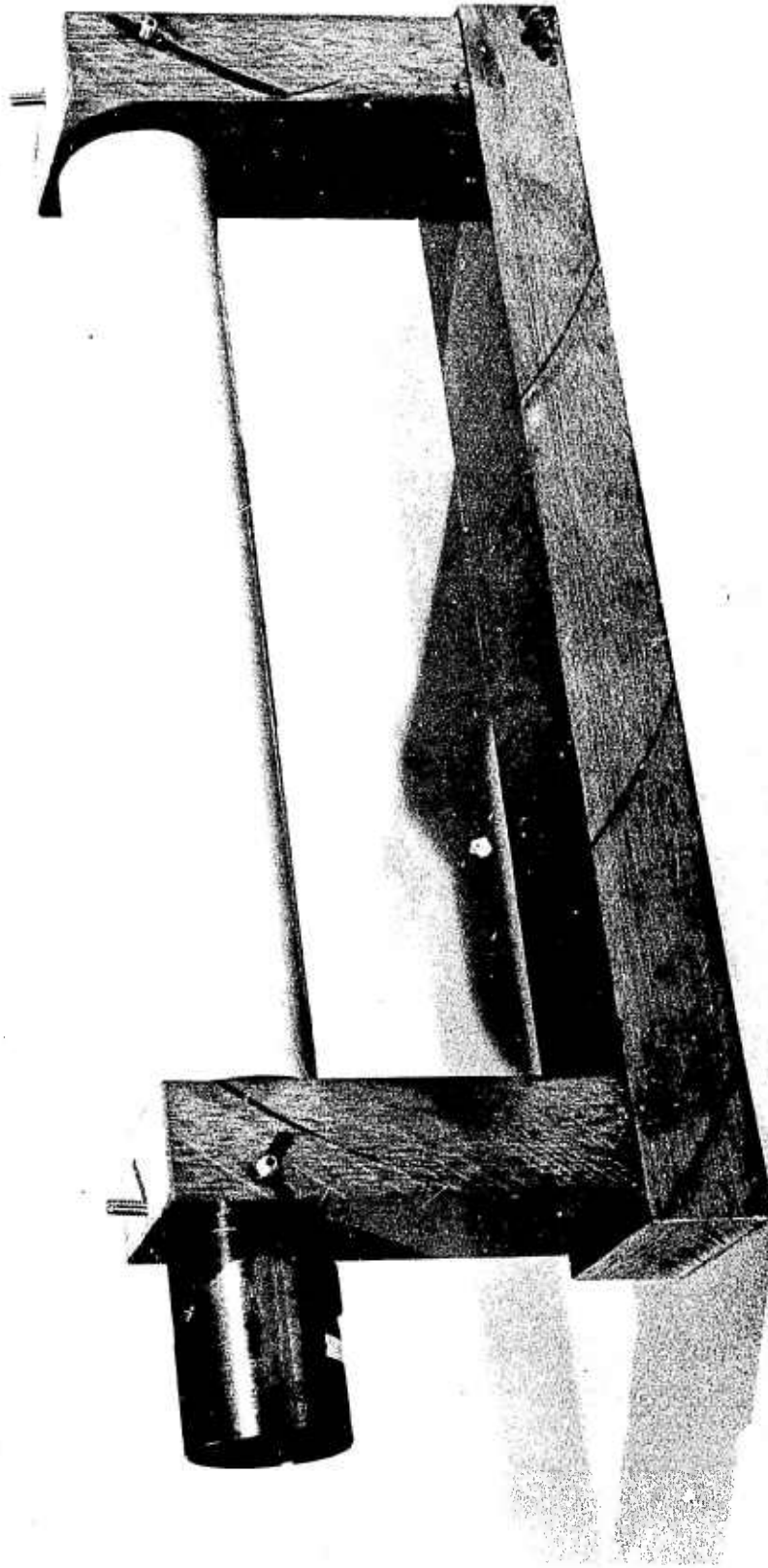


Fig. 10. Optical Isolator

operation is limited to only a few seconds at a time. There is a polarizing prism at each end of the isolator, and the maximum optical transmission is about 70%.

An SFS-6 glass rod is on order, and it will be used later.

#### B. FLUORESCENCE MEASUREMENTS

Since energy transfer across the fluorescence linewidth may depend upon the output wavelengths of the perturbing and probe lasers, and on the fluorescence line of the interaction amplifier, it is desirable to have some versatility or choice in wavelengths to carry out the investigation. The wavelengths of laser oscillation usually occur very close to the peak of the fluorescence curve so that a knowledge of the fluorescence curves of available materials is desired. An inquiry revealed that American Optical Company who supplied most of the Nd-doped glasses could not provide exact fluorescence curves on each sample; they stated that the curves on our samples should be close to each other. Thus it was felt necessary to undertake fluorescence measurements on the commercially available samples. The excitation was confined to the most efficient pump bands by using filters. The measurements were made on a 1-meter Czerny-Turner scanning spectrometer manufactured by Jarrell-Ash. A schematic layout of the experimental setup is shown in Figure 11. The detector was a 7102-S1 photomultiplier tube cooled by dry nitrogen gas flowing through a 77°K liquid nitrogen bath.

A typical trace of the fluorescence curve in the vicinity of 10,600 Å is shown in Figure 12. Several glasses were measured at different scanning rates of the spectrometer and the results are given in Table I. The fluorescence peak wavelength was found to be a function of Nd concentration in light barium crown glass, and this function is plotted in Figure 13.

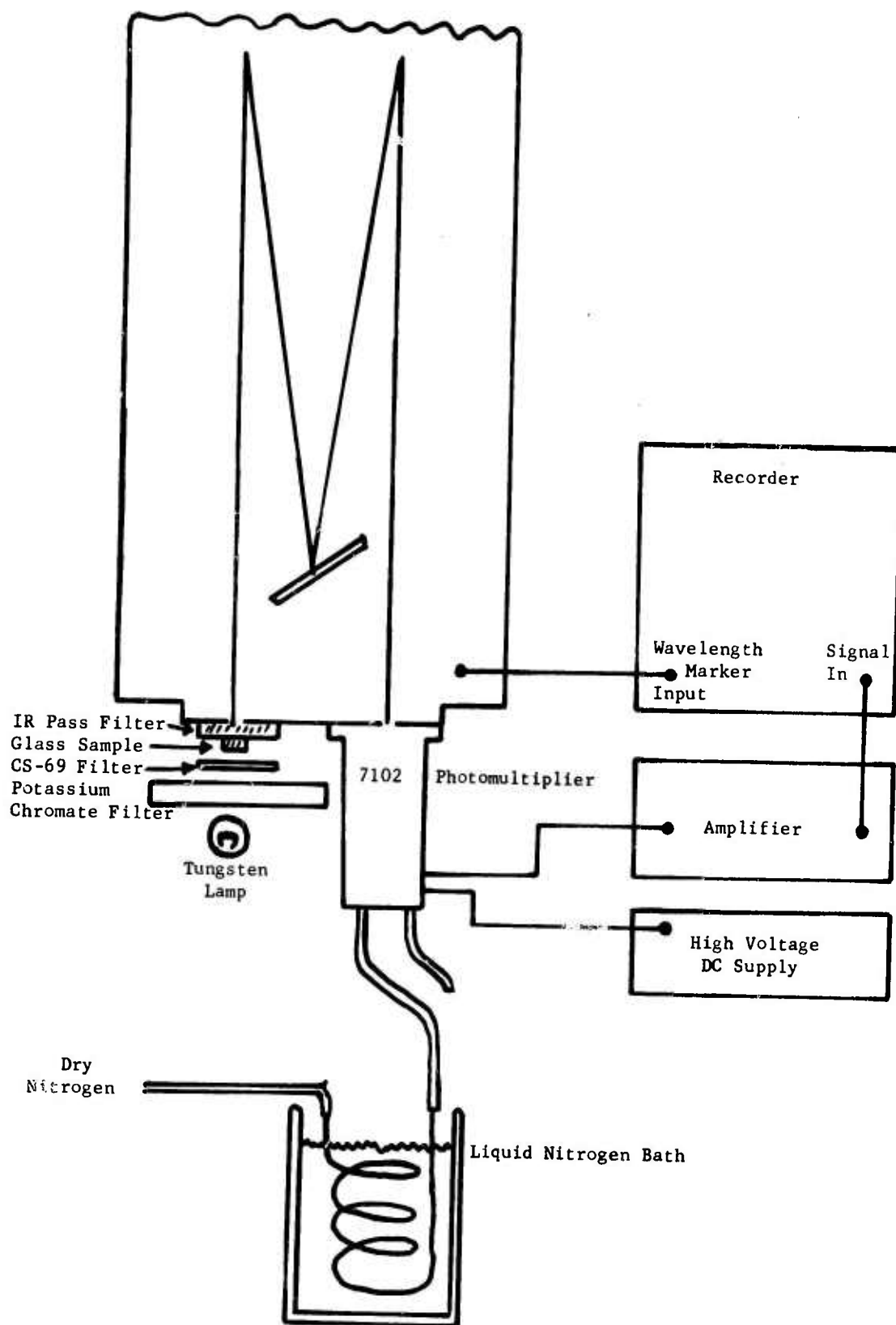


Fig. 11. Schematic of Experimental Layout for Fluorescence Measurements on Samples of Neodymium Doped Glass

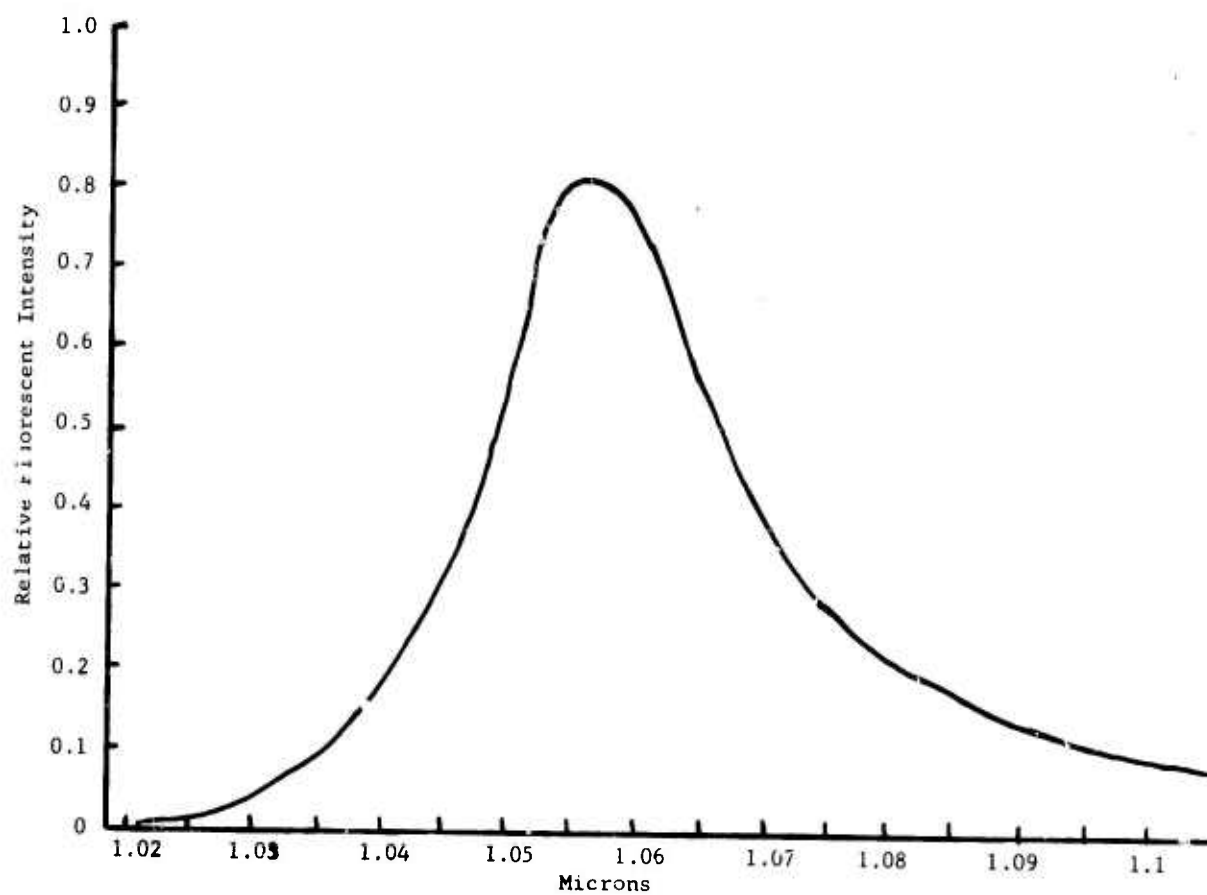


Fig. 12. Typical Neodymium Doped Glass Fluorescence in Vicinity of 1.06 Microns for American Optical 0835 Glass

TABLE I

Fluorescence Data on Commercially Available Nd-Doped Laser Glass

<u>Glass No.</u>	<u>Host</u>	<u>Doping</u>	<u>Fluorescence Peak</u>	<u>Fluorescence Line Width @ Half Power</u>	<u>Fluorescent Lifetime</u>
A.O. 1843	Lt. Ba. Crown	6%	10569.0 Å	210 Å	530
A.O. 0835	Lt. Ba. Crown	5%	10567.0 Å	207 Å	570
A.O. 1020	Lt. Ba. Crown	3%	10563.0 Å	205 Å	640
A.O. 1838	Lt. Ba. Crown	2%	10562.0 Å	200 Å	680
A.O. 1854	Lt. Ba. Crown	1%	10561.0 Å	195 Å	715
A.O. 1953	Lt. Ba. Crown	1/2%	10560.0 Å	190 Å	735
A.O. 1720	Rubidium-Si	6%	10558.0 Å	172 Å	720
A.O. 1689	Rubidium-Si	4%	10562.0 Å	175 Å	780
Schott S-LG56	Silicate	3%	10560.0 Å	215 Å	650 $\mu$
Schott S-LG55	Lt. Ba. Crown	5%	10562.5 Å	205 Å	600 $\mu$
E.K. ND-11	Silicate	2%	10592.0 Å	220 Å	360 $\mu$



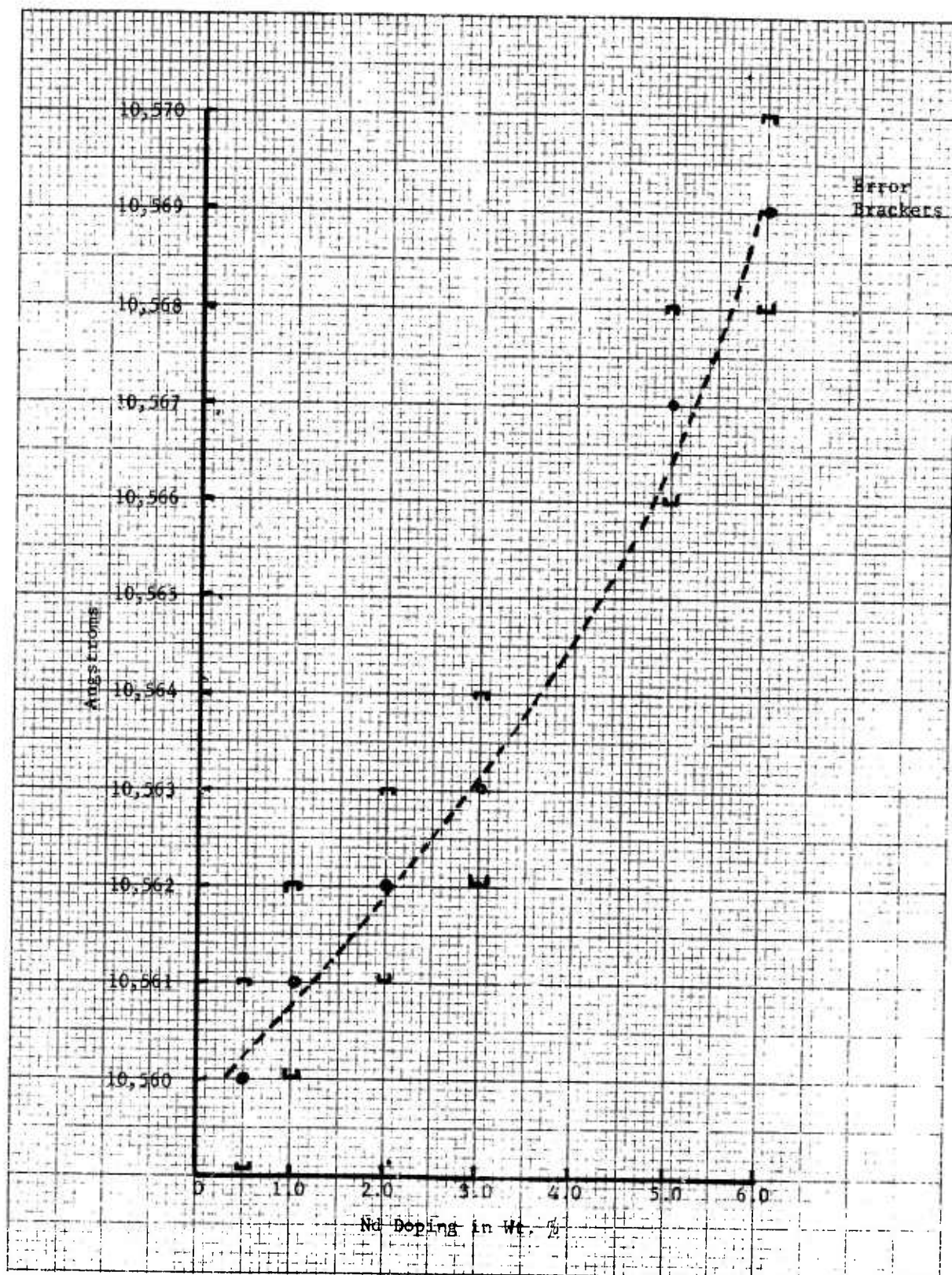


Fig. 13. Fluorescent Emission Peak as a Function of Nd Doping for American Optical's Light Barium Crown Laser Glass

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13. ABSTRACT This is a semi-annual report on investigations of cross relaxation between neodymium ions in laser glass. Work performed during the last six months is described.		

14. KEY WORDS	LINK A		LINK B		LINK C	
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Neodymium Glass Laser Interaction Study Energy Transfer Rare Earth Ions Cross Relaxation						

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